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TIDAL SCATTERING OF STARS ON SUPERMASSIVE BLACK HOLES IN GALACTIC CENTERS

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ABSTRACT

Some of the mass that feeds the growth of a massive black hole (BH) in a galactic center is supplied by tidal disruption of stars that approach it on unbound, low angular momentum orbits. For each star that is disrupted, others narrowly escape after being subjected to extreme tidal distortion, spin-up, mixing and mass-loss, which may affect their evolution and appearance. We show that it is likely that a significant fraction of the stars around massive BHs in galactic centers have undergone such extreme tidal interactions and survived subsequent total disruption, either by being deflected off their orbit or by missing the BH due to its Brownian motion. We discuss possible long-term observable consequences of this process, which may be relevant for understanding the nature of stars in galactic centers, and may provide a signature of the existence of massive BHs there.

Subject headings: black hole physics — galaxies: nuclei — Galaxy: center — Galaxy: kinematics and dynamics — stars: kinematics — stars: rotation

1. INTRODUCTION

A massive black hole in a galactic nucleus grows by accreting matter from its surroundings, some of it in the form of stars that approach it on low angular momentum orbits (loss-cone orbits). When the BH mass m is sufficiently small so that its tidal radius $r_t \propto m^{1/3}$ is larger than its Schwarzschild radius $r_S \propto m$ ($m \lesssim 10^8\,M_\odot$ for the disruption of solar type stars), the star is tidally disrupted before crossing the event horizon. The accretion of stellar debris from such events may give rise to observable "tidal flares" (Frank & Rees 1976). Various authors estimated the rates, timescales, luminosities and spectra of the flares (Ulmer, Paczyński & Goodman 1998; Ulmer 1999; Syer & Ulmer 1999; Magorrian & Tremaine 1999; Ayal, Livio & Piran 2000). There is to date only marginal evidence for the detection of tidal flares (e.g. Renzini et al. 1995; Komossa & Bade 1999; Komossa & Greiner 1999).

In this *letter* we propose another tidal process whereby the BH may reveal its presence. We consider the fate of stars that narrowly escape tidal disruption by the central BH after being subjected to extreme tidal distortion, spin-up, mixing and mass-loss during periastron passage. The total mass in such stars is comparable to that in stars that are disrupted, and therefore also to $(f_t/f_m)\,m$, where f_t is the mass fraction of the BH that originates in tidally disrupted stars, and f_m is the fraction of a disrupted star's mass that is ultimately accreted ($f_m \lesssim 0.5$, e.g. Ayal et al. 2000). The ratio f_t/f_m is significant for a low mass BH ($m \lesssim 10^7\,M_\odot$) that accretes from a low-density galactic nuclear core, where mass loss from stellar collisions is small. Murphy, Cohn & Durisen (1991) found $f_t/f_m \sim 0.15$ in Fokker-Planck simulations of the growth of a low mass BH in a galactic nucleus (their model 4B), assuming polytropic stellar models for estimating the collisional mass loss. More recently, Freitag & Benz (2001, in preparation) found $f_t/f_m \sim 0.25$ for the same galactic nucleus model using Monte-Carlo simulations with more realistic stellar models, which are more centrally concentrated than polytropes, and therefore lose less mass in collisions. They also find f_t/f_m as high as ~ 0.65 for low-density nuclei where the stellar mass function is weighted toward low-mass stars.

Dynamical analyses of the scattering of stars into loss-cone orbits (Lightman & Shapiro 1977; see Magorrian & Tremaine 1999 for numeric examples) show that tidally disrupted stars in galactic nuclei are typically on slightly unbound orbits relative to the BH and that they are predominantly scattered into the loss-cone from orbits at the radius of influence of the BH, $r_h \equiv Gm/\sigma^2$, where σ is the velocity dispersion far from the BH. The stellar mass that is enclosed within r_h is comparable to m. The scattering timescale is shorter than the dynamical timescale, and so the stars are scattered in and out of the loss-cone several times during one orbital period. Following the first close passage near the BH the stars are on very eccentric orbits with apoastron $\lesssim 2r_h$, and so there is a considerable chance that they will be scattered again out of the loss-cone before their next close passage, and thus avoid eventual orbital decay and disruption.

The survival probability is further increased by the Brownian motion of the BH relative to the dynamical center of the stellar system. In a system composed of stars with a typical mass M and radius R and a low mass BH, which evolve in an initially constant density core of radius $r_c \sim r_h$, the amplitude of the Brownian fluctuations is much larger than the tidal radius, $\langle\Delta r\rangle/r_t \sim (r_c/R)\,(M/m)^{5/6} \gg 1$ (Bahcall & Wolf 1976). The Brownian motion proceeds on the dynamical timescale of the core, which is comparable to the orbital period of the tidally disturbed stars. While these results strictly apply only if the BH is embedded in an isothermal system, which is not the case in the GC, they are expected to hold

generally to within an order of magnitude. The orbits of the tidally scattered stars take them outside of r_h, where they are no longer affected by the relative shift between the BH and the stellar mass. Therefore, on re-entry into the volume of influence, their orbit will not bring them to the same peri-distance from the BH. Both the random motion of the BH and the scattering off the loss-cone by two-body interactions are expected to increase the survival fraction f_s to a significantly high value (Fig. 1). More detailed calculations, which integrate over the orbital distribution, are required to confirm these qualitative arguments.

The cross section for a close passage with a peri-distance $\leq r_p$ scales as r_p for stars on nearly parabolic orbits (Hills 1975; Frank 1978). It then follows that the number of stars on nearly loss-cone orbits ($r_t \lesssim r_p \lesssim 2r_t$) is comparable to the number of disrupted stars, and so the mass fraction associated with stars in the volume of influence that have undergone extreme tidal disturbance, $(f_t/f_m)\,f_s$, is significant.

2. MODEL

The tidal interaction between the star and the BH is described in the reduced mass system where the star, of mass M and radius R, is stationary and the BH approaches it on an unbound orbit with a peridistance r_p. The tilde symbol is used to denote quantities expressed in the units where $G = M = R = 1$. In these units $\widetilde{\Omega} = 1$ is the centrifugal break-up angular frequency and $\widetilde{E} = 1$ is the star's binding energy up to a factor of order unity. High rotation is the longest lasting dynamical effect of a hyperbolic tidal interaction that does not end in capture, and so we will use the spin-up of the star by the tidal encounter, $\Delta\widetilde{\Omega}$, as a measure of the long-term effects on the star. A general treatment of spin-up by hyperbolic encounters can be found in Alexander & Kumar (2001), where it is applied to star-star tidal interactions. Here we apply the formalism to the star-BH interaction.

The tidal disruption radius for slightly hyperbolic orbits is $\widetilde{r}_t \simeq \widetilde{m}^{1/3}$ in the limit $\widetilde{m} \gg 1$. It is convenient to parameterize the tidal interaction in terms of the the penetration factor $\beta = \widetilde{r}_t/\widetilde{r}_p$. The linear tidal coupling coefficients T_l are functions of the parameter $\eta = \widetilde{r}_p^{3/2}/\sqrt{1+\widetilde{m}}$, where $\eta \simeq \beta^{-3/2}$ in the limit $\widetilde{m} \gg 1$, and of the eccentricity of the orbit $e = 1 + 2\widetilde{r}_p\widetilde{E}_o/\widetilde{m}$, where $\widetilde{E}_o$ is the orbital energy of the 2-body reduced mass system. The spin-up due to the transfer of angular momentum from the orbit by the tidal interaction is related to the energy transfer by $\Delta E = I\Omega_p\Delta\Omega$, where Ω_p is the relative angular velocity at periastron, I is the star's moment of inertia, and rigid body rotation is assumed (Goldreich & Nicholson 1989; Kumar & Quataert 1998). On parabolic orbits $\Delta\Omega$ is independent of m to leading order in the multipole expansion, and can be expressed as (e.g. Press & Teukolsky 1977)

$$\Delta\widetilde{\Omega} \simeq \frac{T_2(\beta^{-3/2})}{\sqrt{2}\widetilde{I}}\beta^{9/2}\,. \tag{1}$$

The linear analysis of the spin-up breaks down as $\widetilde{r}_p$ decreases and $\Delta\widetilde{\Omega}$ approaches 1. At first $\Delta\widetilde{\Omega}$ increases faster than predicted by the linear analysis, but then it peaks at the onset of mass-loss as the ejecta carry away the angular momentum. In the results presented here we do not correct for the non-linear effects, and so formally very high values of $\Delta\widetilde{\Omega}$ should be understood as indicating any combination of mass-loss, mixing or spin-up effects. The tidal coupling coefficients can be calculated numerically for any given stellar model. In our analysis we will use two stellar models: a $n = 3/2$ ideal gas polytrope, and a solar model (Christensen-Dalsgaard et al. 1996).

We demonstrate the tidal scattering effect by considering the fate of a star on a circular orbit at an initial radius $r_i = r_h$ that loses angular momentum, but not energy, in a 2-body interaction and is deflected into a near loss-cone orbit with peri-distance $r_t < r_p \ll r_i$. We assume for simplicity that the stellar mass within r_i equals the BH mass, that it is negligible within r_p, and that its distribution is proportional to $r^{-\alpha}$ ($\alpha \neq 2,\,3$). It then follows from energy conservation on orbits in a spherical mass distribution that the orbital energy of the reduced mass system at $\widetilde{r}_p$ (i.e. excluding the potential of the stellar cluster) is

$$\widetilde{E}_o = \frac{1}{2-\alpha}\left(\frac{\widetilde{m}}{\widetilde{r}_i}\right)\,, \tag{2}$$

and the eccentricity is

$$e = 1 + \frac{2}{2-\alpha}\left(\frac{\widetilde{r}_p}{\widetilde{r}_i}\right)\,. \tag{3}$$

3. RESULTS

We apply our model to the $3\times10^6\,M_\odot$ BH in the Galactic Center (GC), which is of particular interest because present-day observations can already resolve individual stars very close to the BH (Genzel et al. 1997; Ghez et al. 1998). The BH in the GC is surrounded by a 2-body relaxed cusp with $\alpha \sim 1.5$ and has a radius of influence of $r_h \sim 3.6\,\mathrm{pc}$ (Alexander 1999). For the BH in the GC, $r_t > 10r_S$ for a solar type star, and so general relativistic corrections can be safely neglected (Laguna et al. 1993). Figure 2 shows the cumulative values of the ratio between the rate of near loss-cone encounters ($r_p > r_t$) and the total rate of disruptive encounters, the orbital period after the first periastron passage, and the apoastron distance after the first periastron passage, all as functions of $\Delta\widetilde{\Omega}$. The orbits have $\widetilde{E}_o = 0.04$, but are still effectively parabolic, with $1 < e < 1 + 10^{-5}$. For the solar stellar model, the orbital energy remains positive after the first periastron passage for all values of $\Delta\widetilde{\Omega} < \Delta\widetilde{\Omega}_b = 0.43$ ($r_p/r_t > 1.13$), which corresponds to unbound *and* tidally disturbed stars (defined here as having $1/2 < \Delta\widetilde{\Omega}/\Delta\widetilde{\Omega}_b < 1$) of total mass $0.16\,(f_t/f_m)\,f_s m$. For the polytropic stellar model, which is less centrally concentrated and therefore more easily perturbed by the tidal interaction, the orbital energy remains positive after the first periastron passage for all values of $\Delta\widetilde{\Omega} < 0.28$ ($r_p/r_t > 1.70$), which corresponds to unbound tidally disturbed stars of total mass $0.19\,(f_t/f_m)\,f_s m$. The plots of the orbital period and apoastron radius confirm that the qualitative arguments presented in §1 hold for all but the closest periastron passages.

4. DISCUSSION

We have argued that a significant fraction of the stars around a supermassive black hole in a galactic center experience considerable spin-up, due to extreme tidal interactions with the central BH. Unlike the star–star tidal interactions considered by Alexander & Kumar (2001), which

also lead to high rotation, this mechanism does not require an extremely high stellar density. We further note that the tidally disturbed stars will remain in the galactic center even after tidal scattering ceases in the later phase of the BH growth when its mass exceeds $\sim 10^8\,M_\odot$ and $r_S > r_t$. Assuming $f_s \sim 0.5$, $f_t/f_m \sim 0.25$ and solar type stars, and considering only orbits that are unbound to the BH after the first periastron passage, we estimate that the Galactic Center contains 10^{4-5} stars that have survived an extreme tidal interaction with the central BH.

We now examine briefly potential observational signatures of such interactions. The effects of rotation on stellar evolution have been studied extensively by a number of authors (see e.g. Maeder & Meynet 2000; Heger & Langer 2000, and references therein). Here we want to concentrate in particular on a few observable effects: (1) The luminosity, (2) abundance anomalies, and (3) colors. Rotationally induced mixing results in higher bolometric luminosities for a given mass, due to the increase in the mean molecular weight μ, and in the convective core size. Mixing also brings the products of hydrogen burning to the stellar surface. Thus, one can expect enrichment in ^{4}He, ^{14}N, ^{13}C, and ^{26}Al, and depletion in ^{12}C, ^{16}O, ^{15}N. Combining these two effects, one of the consequences of high rotation rates is stronger abundance anomalies in more luminous stars. Interestingly, these were precisely the effects observed by Carr, Sellgren & Balachandran (2000), in their abundance measurements of the M supergiant IRS 7 in the Galactic center. The low C and O and high N abundances indicate that IRS 7 has undergone mixing in excess of the values predicted by standard models (or observed in other supergiants like αOri). In fact, the observed abundances have prompted Carr et al. to conclude that "extra mixing induced by rapid rotation may indeed be the fundamental difference between the evolution of massive stars in the Galactic center and those elsewhere in the Galaxy." The third effect is relevant particularly to stars that would have otherwise (with no tidal spin-up) been red supergiants or Asymptotic Giant Branch (AGB) stars. The envelopes of such stars (particularly the latter) are relatively loosely bound to their cores. Consequently, even modest amounts of tidal interaction and spin-up lead to a loss of all or a part of the envelope (e.g. Livio 1994). The stripped, more compact star will thus become blue. In fact, this mechanism has been proposed to explain the existence of a strange group of very blue stars in the globular cluster M15 (De Marchi & Paresce 1996), and the colors of Sk $-69^\circ\,202$, the progenitor of SN1987A (e.g. Woosley 1988). Our calculations therefore predict that the stellar population in galactic centers will exhibit a paucity in red giants, and will rather be relatively rich in blue stars. Concentrations of blue stars around the central BH are found in both the Galactic Center (Genzel et al. 1997) and in M31 (Lauer et al. 1998). Many of the blue stars are predicted to be on elongated ("radial") orbits. Observations of the Sgr A* stellar cluster in the Galactic center appear to be consistent with this prediction (Genzel et al. 2000), although the orbital solutions are still quite uncertain (Ghez et al. 2000).

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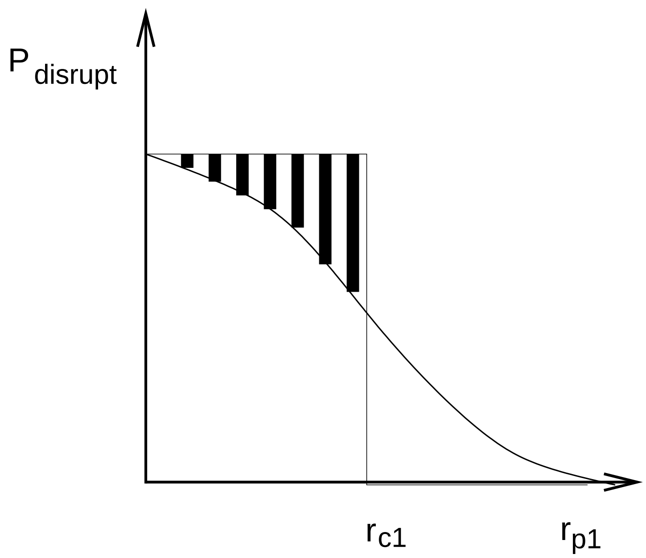

FIG. 1.— A schematic representation of the change in the disruption probability of a tidally disturbed star as function of the first peri-distance r_{p1} when stochastic processes are included. For an isolated 2 body system (i.e. no other stars present) there exists a critical first peri-distance r_{c1} such that a star passing at $r_p < r_{c1}$ will ultimately be tidally disrupted, and conversely, a star passing at $r_p > r_{c1}$ will survive subsequent close passages. When processes such as scattering and the BH Brownian motion are included, some of the stars with $r_p < r_{c1}$ will survive (hatched area).

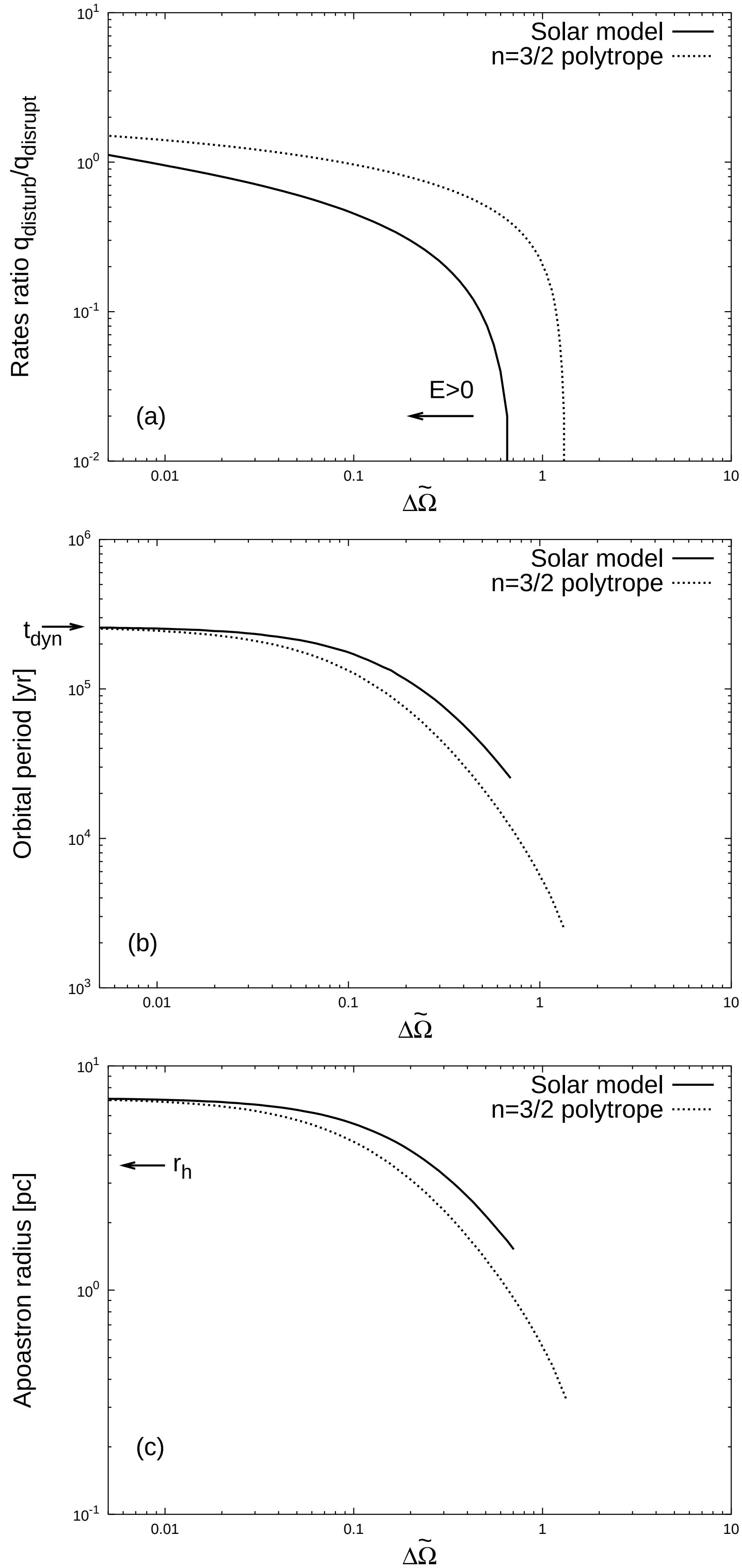

FIG. 2.— (a) The ratio between the rate of stars that undergo extreme tidal disturbance and those that are tidally disrupted in a model of the GC ($M_{\rm BH} = 3 \times 10^6\, M_\odot$, $r_1 = r_h = 3.6\,{\rm pc}$, $\alpha = 1.5$). The arrow marks the range of $\Delta\widetilde{\Omega}$ where the star remains unbound to the BH after the first periastron passage. (b) The orbital period after the first periastron passage. The arrow marks the orbital period at the radius of influence. (c) The apoastron distance after the first periastron passage. The arrow marks the BH radius of influence.